Experiences with Computer-Based Patient Monitoring

Third Becton, Dickinson and Company Oscar Schwidetzky Memorial Lecture

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As the telescope has provided man with the ability to see distant objects and the microscope has allowed him to see things that are ever smaller, so a new tool, the general purpose digital computer, has become a means for extending his intellectual powers to see the relationship among many things and to reduce this relationship to significant generalities in a short time.

Because of the complexity of living things with which a doctor must deal, perhaps no profession stands to gain more from the use of this tool than medicine. It provides the key by which we may reduce the art to a science and, in the process, eliminate that which is useless and unnecessary in the practice of medicine, and through automation extend to everyone the benefits of new knowledge when acquired. In this presentation I hope to convince you of the truth of these general statements by describing our experiences in the development of a computer-based patient-monitoring system.

In 1952, in the laboratory of Dr. Earl Wood at the Mayo Clinic, we developed a method for calculating stroke volume from the contour of a central arterial pressure waveform.[1] Not only has this method become the core of our physiological monitoring system, but it was through work with a project growing out of this study that I first became aware of and interested in computers as a tool for physiologic research. I will briefly describe the sequence of this involvement since I think it illustrates well the way in which computers can provide not just numbers but insight:

Early Studies of Waveform—In the development of the pressure pulse method of stroke volume estimation just referred to, it was assumed for purposes of simplification that a pressure wave is transmitted from the root of the aorta peripherally without distortion. As a matter of fact, the wave is distorted, with some increasing amplitude of peak systolic pressure as it moves

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outward and with the development of one or more secondary oscillations in diastole. In an attempt to understand this phenomenon, I assumed the waveform was a repetitive phenomenon which could be reduced to a Fourier series and represented by a fundamental and harmonics of particular amplitudes and phase relationships.

Hand calculation of a Fourier series representation of an arterial pressure wave is a tedious process. One day, having completed such an analysis on a central and peripheral arterial waveform from the same heart beat, I plotted the ratio of the downstream amplitude to the upstream amplitude—that is, the relationship of the output to the input—for each frequency, and noted that this ratio was 1 for the fundamental but increased to approximately 1.5 at 4½ cps, and then fell to a very small fraction by 10 cps. Such a plot is called a transfer function, and this transfer function of a segment of artery resembled the transfer function of a tuned circuit in that the system was transferring certain frequencies much more readily than others. This observation suggested the possibility of building an electric circuit which could mimic the behavior of the artery. Such a circuit was constructed and tested in the following way:

Development of Waveform Visualization—Simultaneous measurements were made of the central aortic pressure and the peripheral artery pressure, using strain gauge transducers. The output of the transducer recording central aortic pressure was a voltage proportional to this pressure and was used as the input voltage to the tuned circuit. The resonant frequency and damping coefficient of the circuit was then adjusted until the output waveform from the tuned circuit resembled as closely as possible the output waveform from the arterial system. These two waveforms were displayed continuously on a dual-beam oscilloscope for comparison. When the circuit was generating the same waveform as the artery, with both systems having the same input, the parameters of the circuit could be used to describe the corresponding parameters of the artery.[2]

A study on approximately 80 patients showed that the resonant frequencies so determined had a correlation with age of 0.68 and ranged from 3.5 cps at age 20 to 7 cps at age 70.[3] This was our first experience with a special-purpose analog computer and stirred an interest in computers which has dominated the activities of our laboratory over the past 12 years.

Now let me describe the method for estimating stroke volume from the central aortic pressure wave, which plays such a central role in our computer-based monitoring system.

Analysis of Stroke Volume—Stroke volume may be divided into two parts: That which runs out of the arterial bed during systole, the systolic drainage, and that which remains in the arterial bed at the end of systole to run off during the subsequent diastole, the diastolic drainage. On the assumption that the pressure wave travels undistorted down the system, it is possible to estimate the pressure at each point down the system at the onset of systole and at

★ HOMER R. WARNER, M.D. represents an effective blend of many disciplines. He is basically an Internist who has become an Established Investigator of the American Heart Association, Research Professor of Surgery at the University of Utah, Professor and Chairman of the Department of Biophysics and Bioengineering at the University of Utah, and Editor of the new journal, *Computers and Biomedical Research*. In addition, he is Director of the Cardiovascular Laboratory at the Latter-Day Saints Hospital in Salt Lake City. This Society was honored to have Dr. Warner present the accompanying paper as the Third Annual Oscar Schwidetzky Memorial Lecture, sponsored by the Becton-Dickinson Company of Rutherford, New Jersey.

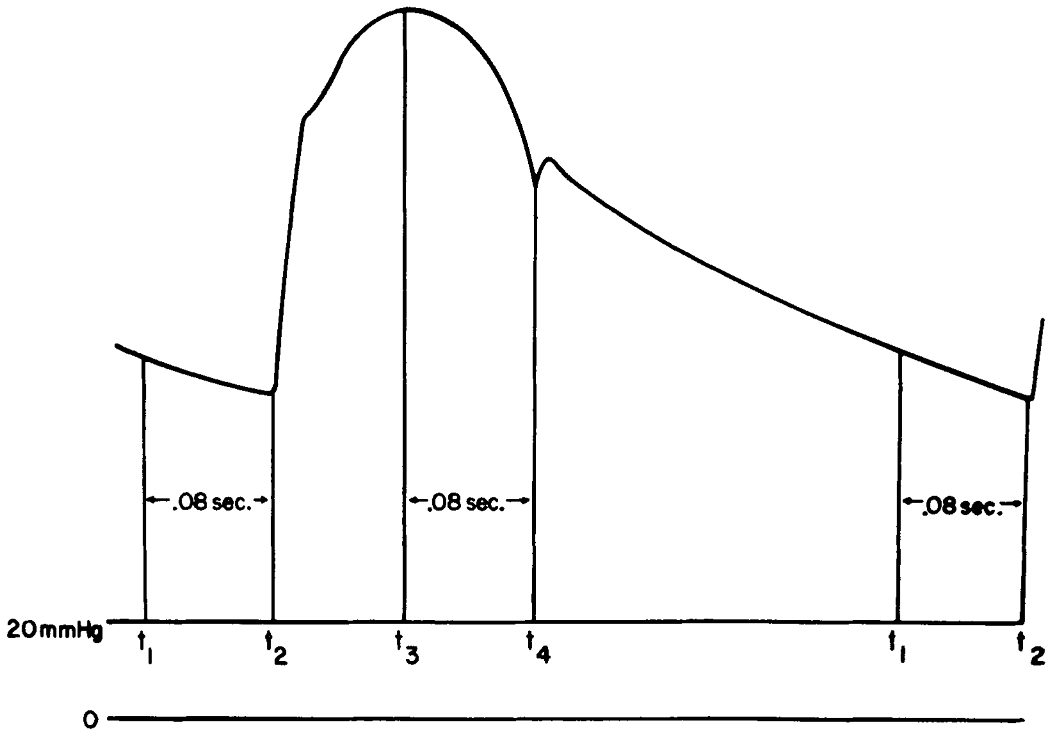

FIG. 1. Central arterial pressure wave, showing key points used in stroke volume calculation.

the end of systole by examining points back on the central waveform, a distance proportional to the time required for the waveform to be transmitted from where it is recorded in the central aorta to the site of interest (fig. 1). Here the arterial system is arbitrarily defined as the length of aorta over which the wave would travel in 80 msec.

The stored volume, or diastolic drainage, is proportional to the difference in pressure integrated over this 80-msec. segment before and at the end of systole, if the pressure is proportional to the volume in the range of the pulse pressure being recorded. This proportionality constant is determined once in each individual by measuring cardiac output by an independent method, since aortic properties, both size and distensibility, vary greatly from one individual to the next.

A second constant, relating pressure to flow, need not be determined explicitly. Since this cancels out in the equation, all that is required is the ratio of flow in systole to flow in diastole. Thus, the method is independent of changes in peripheral resistance.

Figure 2 shows a cross-plot of cardiac output measured by the pressure pulse method beat-by-beat compared against the cardiac output determined from beat-by-beat measurements, using an electromagnetic flowmeter on the ascending aorta of a dog. During these measurements, the dog is standing on a treadmill and is subjected to a variety of stresses, including exercise and infusion of vasopressors and vasodilators

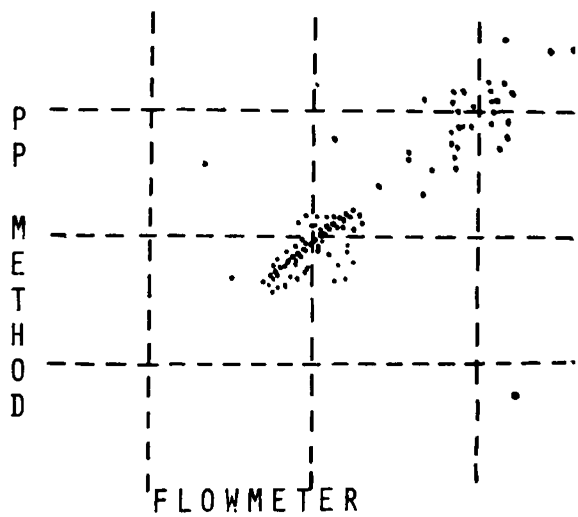

FIG. 2. Cross-plot of beat-by-beat cardiac output values measured by flowmeter and by pressure pulse method.

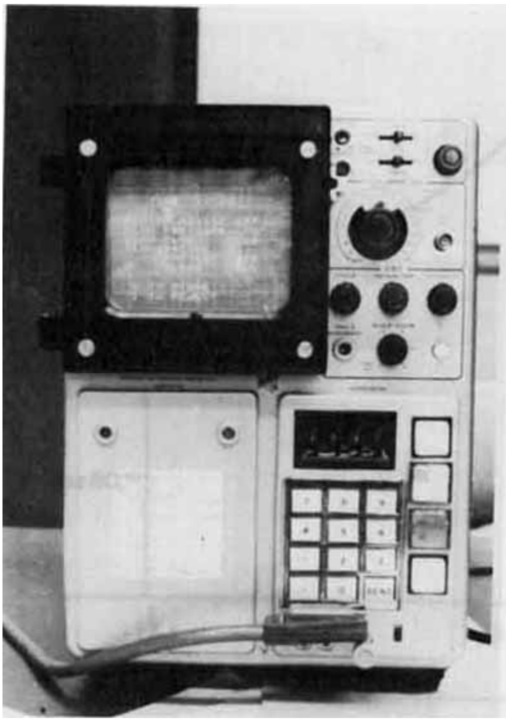

FIG. 3. Equipment for communicating with the computer from a remote site.

through a catheter in the descending aorta. Correlation between the two methods is 0.97.[4]

Although beat-by-beat comparisons against a flowmeter could not be made in humans, mean values of cardiac output by the pressure pulse method were compared against cardiac output by the dye method, which requires 20 to 30 seconds. The dye method was used to calibrate the pressure pulse method with the patient at rest; then norepinephrine was infused intravenously to elevate the arterial pressure, and measurements were also made during exercise. The agreement between the two methods was as good as the agreement between repeat determinations by the dye method.

Contributions of Computer—The experiments just described would not have been possible without the computer. It was necessary to develop a method for performing these calculations beat-by-beat that was not only faster than the manual method but also more accurate and objective. This is now accomplished by feeding the output voltage from a strain gauge pressure transducer to an analog-to-digital converter. This device converts this electric signal to a number proportional to the magnitude of the voltage, 200 times per second.

A program has been written for the Control Data 3200 computer which permits it to accept continuously this string of numbers, examine the sequence of numbers to determine the beginning and end of systole on each heart beat, and carry out the calculation indicated earlier in the equations presented. The answers are then displayed by the computer on an oscilloscope through the use of a 2-channel digital-to-analog converter which controls the X and Y axis of the oscilloscope to generate graphs, letters, and numbers on its face. Thus, the loop is closed, allowing the experimenter to connect his transducer direct to a system and receive back from that system the derived data he desires.

Figure 3 shows the remote station through which the experimenter communicates with the computer. This is built around a Tektronix® memory oscilloscope, which is used as the display device. The program is controlled through a 4-digit octal switch and a 12-digit decimal keyboard. Pressing any button causes the computer to be interrupted to interpret the code sent by that key. A series of eight lights is provided to inform the operator of the computer status and the status of his program.

Design of a system for servicing physiologic needs presents some interesting problems. Computing speed is essential to accomplish certain tasks and yet, on the other hand, some physiologic events occur very slowly compared to the computing time required to keep up with them. Thus, if the user is to have the computer when he needs it for this kind of work, it is necessary, if a computer is to be used efficiently, that a system be devised for rapid switching among programs. Such a scheme, called time-sharing, has been implemented on the Control Data 3200 at the Latter-day Saints Hospital in Salt Lake City.

The Time-Sharing Monitor — The time-sharing monitor, called MEDLAB,[5] resides in the memory of the central computer which, in turn, communicates with a variety of peripheral devices. Programs or instructions are entered into the computer initially through a card reader and are then stored on magnetic discs from which they can be called into memory from any of the remote stations. Data on patients in the hospital are stored on magnetic discs also for ready access. When a patient is discharged, his

C.O.	4.16
M.I.	0.97
A.T.	11.50
B.T.	5. 0
M.C.	20. 5
C.V.	1.39

FIG. 4. Information displayed to operator within 1 second after completion of sampling following injection of indocyanine green dye.

record is copied onto a library tape, where it is stored permanently. Program listings and reports are generated on a high-speed printer at the rate of 1000 lines per minute.

The analog-to-digital and digital-to-analog conversion system forms the basic link to the remote stations. Presently there are 19 remote stations in five different hospitals attached to our system. To each of these users operating from his remote station, the computer appears to be under his command and he can operate essentially independently of other users on the system.

The 32,000 words of core memory are allocated as follows to accommodate multiprogramming: In the top 5000 words of memory is the monitor program, which contains not only the instructions that control switching among the programs in memory, swapping of programs in and out of memory, and sampling of data, but also a set of re-entrant subroutines which can be used by any of the user programs to accomplish such tasks as writing on the oscilloscope, converting numbers from binary to decimal, and inserting answers into messages. This latter function considerably reduces the programming the user must do to accomplish his goals.

From four to six real-time programs (up to 2000 words in length for any one overlay), which are actively sampling data, may be in memory at any one time, and programs not sampling may be swapped onto discs temporarily while other programs are being run. The lower part of core memory is reserved for compilation and assembly of new programs and execution of Fortran programs, which may or may not communicate with the real-world through one of the remote stations; those that do carry a higher priority than those that do not, in the sequence in which jobs are executed. The organization of data on the magnetic discs, whether from experimental animals or patients, follows a common format.

Compilation of Data—This file organization is designed to provide for addition of new types of information in the future and still maintain a basic format, so that the same search, edit, and analysis programs can be shared by a wide variety of users. At the start of each file is a count which keeps track of how many entries are currently in the file and where the next word of data is to be stored. Entry of a field of data is preceded and ended by a code which uniquely defines the kind of data and the number of data words in the field. The second word is the time and date, read automatically by the computer from an external clock when the entry is made. Thus, any user may define a new field of any length and add it to this file.

Examples of Data Code—A general program has been written for introducing a

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1WE    101
1PT   52/ 26    39
1RV   84/ 15    20
2RD    100
0RD   97/ 64    77
0RD     93
0C.O.        4.16
 M.I.        1. 1
 A.T.       12.25
 B.T.        4.75
 M.C.       20. 0
 C.V.        1.38
```

FIG. 5. One page of data displayed during edit routine.

variety of physiologic measurements into the computer, which is now in use in several diagnostic heart-catheterization laboratories connected to our system. This permits the user to initialize a file on a patient and call a variety of subprograms to analyze data in any sequence. To do this, a 4-digit rotary switch on the remote console is used. The first digit indicates the type of analysis to be performed. For instance, 0 is an oxygen-saturation measurement, 1 is a pressure wave, 2 is a dye curve, and so forth. The second digit indicates the state of the patient. For instance, 0 means the patient is at rest, breathing room air, 3 means the patient is breathing oxygen during exercise, and so forth. The last two digits are used to indicate the position of the catheter tip in the circulation.

The operator dials the desired code and presses the interrupt. The code is interpreted by the computer and this interpretation is presented back on the oscilloscope for confirmation by the operator. If one or more of the digits was in error, the code is redialed and sent again. Until the same code is sent twice, the program will not proceed. When the data are on the line, (for instance, the pressure to be measured appears free of artifact) the interrupt is pressed once again, and the analysis begins. The results are displayed back immediately to the operator, who may choose to discard the data or save them by writing them on the disc to be included in a later report.

Figure 4 shows the presentation made on the oscilloscope to the operator upon completion of analysis of an indicator-dilution curve. At the bottom is the recorded curve plotted back as milligrams per liter and superimposed on this, the experimental extrapolation carried out by the computer, so that the operator has some means for evaluating the adequacy of the analysis.

At the top are the calculated values: cardiac output is 4.16 L./min. "M.I." is the mitral insufficiency index, which should be 1 or greater in a normal subject, and measures the skewness of the curve; this is a useful empiric index for the presence of mitral insufficiency in the absence of a left-to-right shunt. Next are shown Appearance Time, Buildup Time, Mean Circulation Time, and Central Blood Volume. At any time during the procedure and at the end of the procedure the operator may review and edit the data accumulated on the disc.

Figure 5 shows one page of data presented on the face of the oscilloscope. The "1" on the first line indicates that the patient is exercising and an oxygen saturation reading of 101 was obtained with the catheter tip in the "wedge" position. The next reading is a measurement of pressure in the pulmonary trunk, with the systolic, diastolic, and mean pressures shown. At the bottom is a cardiac output measurement by the dye method.

Pressing a zero causes the next page of data to be presented on the oscilloscope. Values may be deleted or altered by the operator, who may request any number of copies of a printed report upon completion of his editing, including a computer-generated summary of the abnormalities present. Thus, before the catheter is removed from the circulation, the data are completely analyzed, and if any question exists about the significance of some of the data, repeat measurements can readily be made. A direct extension of these technics is their application in the operating room and at the bedside.

Example of Clinical Application—On the afternoon before his surgery, the patient is taken to a special laboratory equipped with a remote computer station, where a tiny central aortic pressure catheter is introduced by a technician. Using a special armboard*

*SAFLEX®, Romney Engineering & Manufacturing Company, Salt Lake City, Utah.

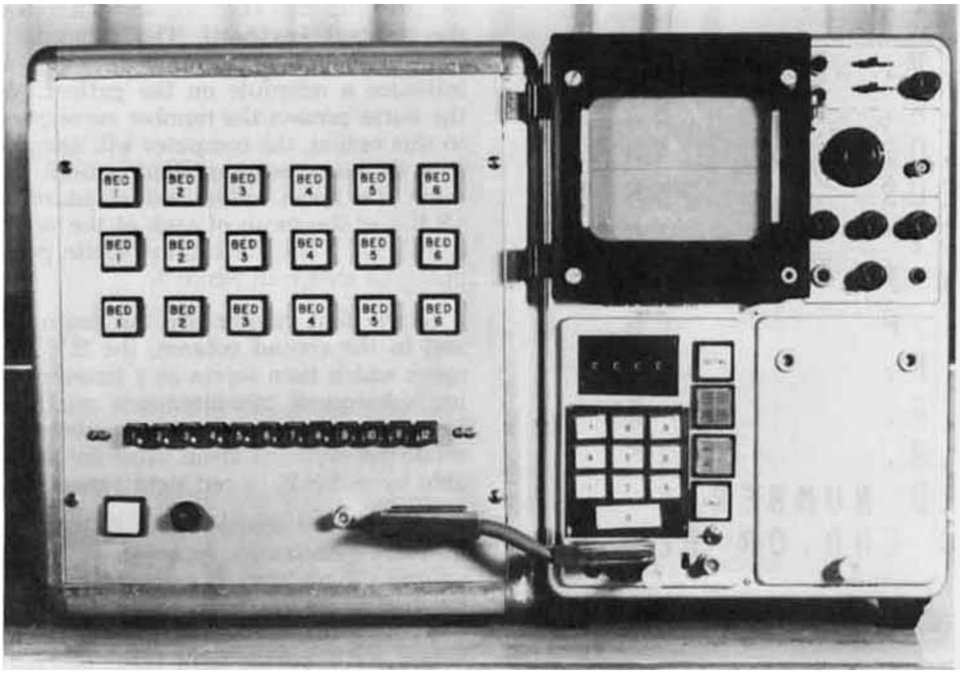

FIG. 6. Remote console located at nurse's station in the intensive care ward.

which is floor-mounted and can be positioned next to any type bed or table, the patient's wrist is extended and local anesthetic is introduced around the radial artery. Then a thin-walled 18-gauge needle, connected by a special catheter assembly* to a strain gauge manometer, is introduced into the artery percutaneously by a technician while she visually observes the pressure waveform on an oscilloscope.

When the needle enters the artery, the solid plastic casing surrounding the catheter is withdrawn, automatically advancing the catheter up the artery to the subclavian. No fluoroscopic control is needed, since the catheter will not pass beyond this point, due to the sharp angulation of the artery and the rigidity of the catheter. When this point is reached, the pressure wave disappears and the catheter is withdrawn 2 cm., where it remains for the rest of the study. The needle is withdrawn from the artery over the catheter and control measurements are performed.

A cardiac output determination may be made by injecting dye into the antecubital vein and sampling through this needle prior to introduction of the catheter. However, in many patients, since changes in cardiac output are of primary interest, no absolute calibration against the dye method is performed. On completion of the control studies, the catheter is removed from the strain gauge, filled with heparin, and dead-ended. The catheter assembly is then taped to the forearm and the patient is returned to his room. These catheters have been left in place as long as 10 days, and in over 400 such procedures, most of which have been done by technicians, no significant complications have resulted.

The next morning the patient goes to surgery, where his catheter is once again connected to a pressure transducer at a remote station in the operating room. Pressure calibration is repeated by sampling the strain gauge output when it is exposed to 0 and 100 mm. Hg pressure from a mercury manometer through a saline flush system. From that point on, the anesthesiologist can obtain a measurement of pressure, stroke volume, heart rate, cardiac output, and resistance by merely pressing an interrupt button on the console at his side and have the results displayed back to him on the oscilloscope of that console.

Other programs developed by Dr. William M. Stauffer, in our laboratory, permit the anesthesiologist to enter other pertinent information during the course of the procedure, such as drugs administered and comments about the patient, which become part

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   17.35
S.V.           52    5
H.R.           83    8
C.O.           44    6
SDUR          235   25
RST            15    4
SY P          106    6
DI P           66    4
V.P.           14
R.A.            2
R.R.           15
BED NUMBER 5
 0 END,OR BED NO.
```

FIG. 7. Display of mean values and standard error of the mean for stroke volume (SV), heart rate (HR), cardiac output (CO), duration of systole (SDUR), resistance (RST), systolic pressure (SY-P) and diastolic pressure (DI-P) measured from central aortic pressure waveform on 64 heart cycles. Mean venous pressure (VP), respiratory amplitude (RA), and respiratory rate (RR) are derived from central venous pressure signal.

of the computer-based record and can be printed out at the end of the operation in the form of an integrated anesthesiology record on this patient.

After surgery, the patient is taken to a 6-bed intensive care ward which contains a remote console, as shown in figure 6.

At the top of this figure is shown a standard remote computer input station with its memory oscilloscope, 4-digit switch, and 12-key decimal keyboard. This scope can be used both for computer writeout and for direct display of pressure or electrocardiographic waveforms from any bed. At the bottom is a second unit containing a bank of lights and a row of pushbutton switches used to indicate the bed from which waveforms are to be displayed. There are three lights for each of the six beds. The green light indicates the computer is actively sampling data from that bed. The red and yellow lights are used to alert the nurse that a change has occurred in the patient occupying that bed.

To initiate a monitoring schedule on a patient, the nurse or doctor presses the call button and then indicates the bed number by pressing the corresponding number on the decimal keyboard. The computer displays a list of options, one of which is to initialize a schedule on the patient. When the nurse presses the number corresponding to this option, the computer will sample the next 64 heart beats on that patient, determine the mean value and standard error (S.E.) of the mean of each of the variables calculated from the central aortic pressure pulse, as shown in figure 7.

In the first column are the mean values and in the second column, the S.E. of the mean which then serves as a basis for judging subsequent measurements on that patient. If any subsequent measurement exceeds the expected mean value for any variable by >3 S.E., a red light turns on.

More subtle changes may be detected if they are systematic. If, for instance, stroke volume differs from its expected mean value by 1 S.E. in the same direction on three successive measurements, a trend is established and a yellow light turns on. When a red or yellow light appears, the nurse or doctor can press that light. which is also an interrupt switch, and cause the computer to display an interpretation of that light back on the memory oscilloscope, as shown in figure 8.

In this case (fig. 8), the variable furthest out of tolerance is diastolic pressure. The last value, measured at 18:06, was 104 mm. Hg, while the baseline value was 88 mm.

```
BED  3
DI P

LAST          18.6
  104
 BASE          18.2
   88
 1  EXPLAIN
 2  REVIEW
 3  IGNORE
 4  NEW BASE
 5  WAVES
```

FIG. 8. Message displayed when the nurse presses red light to explain physiologic variation in a patient.

```
   17.37   17.35
S.V.     53     52
H.R.     77     83
C.O.     42     44
SDUR    231    235
RST      16     15
SY P    109    106
DI P     65     66
V.P.     15     14
R.A.      1      2
R.R.     16     15
BED NUMBER 5
0 BAK,1 FOR,9 DEL
```

FIG. 9. Oscilloscope display under a review data option of program, showing two sets of readings 2 minutes apart for comparison.

Hg. To explain this rise in diastolic pressure, the nurse may choose option 1, allowing her to enter clinical information which she thinks might be pertinent to the physiologic observation. This is entered by indicating whether it is a procedure, a condition, or medication. Following this, an appropriate list under each of these categories is presented and the nurse once again chooses her specific entry from that list. This information is then stored on disc as part of the patient's record for later correlation with the physiologic information.

By pressing option 2, the nurse can review the course of the patient over any arbitrary period of time. Under this option, the data are presented as shown in figure 9. The first column of numbers are the values for each of the variables measured at 17:37, and the second column are the values measured 2 minutes earlier. The user can page forward or backward, displaying values in this fashion to obtain information as to the time-course of events leading up to the physiologic change.

Any data that differ significantly from the baseline values are saved in the patient's file. The scheduling of measurements is done by the computer through an algorithm, which adjusts the interval between samples according to how stable the patient is. For example, if the patient is doing well, the interval between samples is made longer up to a maximum of 16 minutes, but if a change occurs in the patient's condition, that interval is shortened to 2 minutes on the next reading.

Another way in which the data may be reviewed by the nurse or doctor is to request a plot on the oscilloscope of the time-course of one or more variables over a time interval requested by the user. Still another available aid for interpretation of physiologic change is provided through an option which permits the time-course of arterial pressure averaged over 16 heart beats at the time of the last measurement to be displayed on the oscilloscope and superimposed on the waveform recorded at the time of the baseline measurement. Changes in contour of these waveforms have provided useful information in detecting conditions, such as blood loss, at an early stage.

At the end of each 8-hour shift, a summary report is printed for each patient showing the mode values of each variable and the comments entered by the nurses. When a patient is discharged from the ward, his data are copied from disc to library tape and saved for subsequent analysis.

Effects on Personnel—It is interesting to reflect on the changes that have occurred in the attitudes and goals of the people involved in this project. Initially it was hoped that the computer monitoring, by relieving the nurse of some routine measurement duties, might provide her with some free time, and thus decrease the number of nurses required to care for these patients. However, this has not been the case. Even though the nurse is relieved from some of her monitoring and recording duties, she is busier than ever, as is the doctor. The reason for this lies in the fact that they now know much more about their patient, and are forced to make many more decisions than before when they were, to a greater extent, in the dark about what was going on physiologically.

Even though the physiologic data are screened to present only that information which indicates a statistically significant physiologic change, the job of interpreting this change and the intellectual task of deciding what to do about it is one we are not as yet qualified to perform well. Even with 2 years experience with this system, many situations still arise which not only the nurse but also the doctor have difficulty in interpreting. It is for this reason that we are accumulating, in parallel with the physiologic data, as much clinical information as possible, in the hope that in time we will develop sufficient correlative information to permit the computer to assist us in more accurate interpretation of the clinical meaning of the data with which we deal.

Although the monitoring system is continually evolving to include additional variables such as pH, pCO_2, and pO_2, which were recently added, even at this point in time it has proven its usefulness and does contribute to better patient care. Perhaps the best evidence of this is the fact that some surgeons doing open-heart surgery will now postpone a case if, for some reason, the computer monitoring system is not available.

This transition from emphasis on largely routine and somewhat mechanical activities to sometimes difficult intellectual effort is not an easy one for the nurse to make. It does require considerable retraining and shift of emphasis. The advent of the computer can be expected to bring equally drastic changes to the physician as well, as he begins to allocate more and more of the routine aspects of information storage, pattern recognition, and diagnosis to the machine, and finds himself spending more time dealing with creative and sometimes difficult new aspects of the world of medicine.

SUMMARY

A system has been devised and tested for measuring stroke volume, cardiac output, heart rate, peripheral resistance, and other variables on patients prior to, during, and after open-heart surgery which requires only the push of a button to initiate the measurements at any time. These calculations are made from a transducer recording central arterial pressure and sampled 200 times per second by a time-shared digital computer.

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If your aide drives her own car on errands for you, it is extremely important that you are covered by your insurance policy. This fact has just been underscored by a court case in the South. It cost an employer $400,000 when the clerk he sent out for a piece of equipment, injured others in an accident. A $14-a-year rider to your own auto policy would give you up to $300,000 of protection against such a loss.